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P. I. Roger F. Knacke
Astronomy Program
Department of Earth and Space Sciences
State University of New York
Stony Brook, New York 11794-2100
Telephone: (516) 632-8229
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ABSTRACT

This research consisted of a long-range study of the atmospheres of Jupiter and Saturn using the techniques of infrared spectroscopy. The investigations were designed to concentrate on areas that complemented the VOYAGER missions to the outer planets, such as very high spectral resolution. Highlights included observations of the highest resolution 10 μm spectra of Jupiter and Saturn over a broad spectral range, determination of the origin of carbon monoxide (CO) in Jupiter, measurements of the abundances of hydrocarbons such as ethane (C_2H_2), the discovery of germane (GeH_4) in Saturn, the first observation of the element arsenic (in arsine, AsH_3) in a planetary atmosphere, and studies of the structures and dynamics of the atmospheres of Jupiter and Saturn. Three students completed Ph.D. degrees based on research in this project.

CONTENTS

I. <u>Research Summary</u>

The most complete and concise summary of the research accomplished in this project is contained in the ABSTRACTS of the published papers which are given here. The work was also reported at numerous meetings and conferences. All results reported at meetings were subsequently published in refereed literature and are included here.

ETHANE AND ACETYLENE ABUNDANCES IN THE JOVIAN ATMOSPHERE

A. Tokunaga, R. F. Knacke, and T. Owen
Department of Earth and Space Sciences,
State University of New York at Stony Brook

ABSTRACT

New observations of Jupiter in the 755-850 cm^{-1} spectral range have been used in conjunction with radiative-transfer calculations to obtain mixing ratios of ethane and acetylene. The monochromatic absorption coefficient of the central Q branch of the ν_9 fundamental of ethane was measured in the laboratory. The largest mixing ratios for the region above the Jovian tropopause consistent with the observations are $[n(C_2H_6)]/[n(H_2)] = 3 \times 10^{-5}$ and $[n(C_2H_2)]/[n(H_2)] \leq 7.5 \times 10^{-8}$.

The Astrophysical Journal, 209:294-301, 1976 October 1

17-25 MICROMETER SPECTRA OF JUPITER AND SATURN

A. Tokunaga, R. F. Knacke, and T. Owen
Department of Earth and Space Sciences,
State University of New York at Stony Brook

ABSTRACT

Ground-based 17-25 μm spectra of Jupiter and Saturn are compared to intensities computed from current thermal structure models. We obtain good agreement with the continuum of Jupiter for models which incorporate a

temperature inversion, but published models give disagreement with the continuum of Saturn. Upper limit abundances for sulfur and phosphorus in the Jovian atmosphere, as thermodynamically stable species S_8 and P_4, are found to be 0.04 and 2.1 times the solar abundance.

The Astrophysical Journal, 213:569-574 1977 April 15

SIGNAL-TO-NOISE RATIOS OF MULTIPLEXING SPECTROMETERS IN HIGH BACKGROUNDS

R. F. Knacke
NASA Ames Research Center, Moffett Field, California

The relative merits of scanning and multiplex spectrometers have been discussed numerous times[1,2] with reference to gratings, Fabry-Perot spectrometers, and Michelson interferometers. It is common knowledge that the Fellgett advantage of a Michelson spectrometer is fully realized only if the predominant noise source is in the detector or associated electronics. However, in many applications, especially in astronomy, other sources such as backgrounds may contribute significantly to or dominate the noise. In this Letter we estimate the signal-to-noise ratios and the amount of multiplexing gain which can be achieved with the Michelson spectrometer in the presence of both detector and background noise.

Applied Optics, vol. 17, page 684, March 1, 1978

HIGH-RESOLUTION SPECTRA OF JUPITER IN THE 744-980

INVERSE CENTIMETER SPECTRAL RANGE

A. T. Tokunaga
Steward Observatory, University of Arizona

R. F. Knacke
Astronomy Program, Department of Earth and Space Sciences
State University of New York at Stony Brook

S. T. Ridgway and L. Wallace
Kitt Peak National Observatory, Tucson, Arizona

ABSTRACT

Spectra of the central 5" region of Jupiter in the 744-980 cm^{-1} (10.2-13.4 μm) spectral range are presented at 0.05 and 0.28 cm^{-1} resolution. The gases $^{14}NH_3$, $^{15}NH_3$, and PH_3 are observed in absorption, and C_2H_2 and C_2H_6 are observed in emission. A synthetic spectrum which included the opacity from H_2, $^{14}NH_3$, $^{15}NH_3$, and PH_3 is compared with the observations. We conclude that: (1) the $^{14}NH_3$ line profiles are best fitted with a NH_3 density in the troposphere which is 0.5 times the saturated vapor pressure density and an opaque cloud at the 0.56 bar pressure level (T = 140 K); (2) the best fit $^{15}NH_3/^{14}NH_3$ ratio is 0.006 (but may be consistent with the terrestrial ratio within model uncertainties; (3) the $[PH_3]/[H_2]$ ratio is 1-2 x 10^{-7} in the troposphere; (4) the mixing ratios of NH_3 and PH_3 must be highly subsaturated above the tropopause or the temperature inversion is cooler than model predictions; and (5) the intensities of the $^{R}Q_0$ branch of the ν_9 fundamental of C_2H_6 and lines of the R branch of the ν_5 fundamental of C_2H_2 are consistent with previous work.

The Astrophysical Journal, 232:603-615, 1979 September 1

HIGH SPATIAL AND SPECTRAL RESOLUTION 10 μm OBSERVATIONS OF JUPITER

Alan T. Tokunaga
Institute for Astronomy, University of Hawaii

R. F. Knacke
Department of Earth and Space Sciences,
State University of New York at Stony Brook

S. T. Ridgway
Kitt Peak National Observatory, Tucson, Arizona

ABSTRACT

Ten-micrometer spectra of the North Tropical Zone, North Equatorial Belt, and Great Red Spot at a spectral resolution of 1.1 cm^{-1} are compared to synthetic

spectra. These ground-based spectra were obtained simultaneously with the Voyager 1 encounter with Jupiter in March, 1979. The NH_3 vertical distribution is found to decrease with altitude significantly faster than the saturated vapor pressure curve and is different for the three observed regions. Spatial variability in the NH_3 mixing ratio could be caused by changes in the amount of NH_3 condensation or in the degree of the NH_3 photolysis. The C_2H_6 emission at 12 μm has approximately the same strength at the North Tropical Zone and North Equatorial Belt, but it is 30% weaker at the Great Red Spot. A cooler temperature inversion or a smaller abundance of C_2H_6 could explain the lower C_2H_6 emission over the Great Red Spot.

Icarus 44, 93-101 (1980)

THE ABUNDANCES OF CH_4, CH_3D, NH_3, AND PH_3 IN THE TROPOSPHERE OF JUPITER DERIVED FROM HIGH-RESOLUTION 1100-1200 cm^{-1} SPECTRA

Roger F. Knacke and Sang J. Kim
Astronomy Program, Department of Earth and Space Sciences,
State University of New York at Stony Brook

Stephen T. Ridgway
Kitt Peak National Observatory

and

Alan T. Tokunaga
Institute for Astronomy, University of Hawaii

ABSTRACT

High-resolution ($\Delta\nu = 1\ cm^{-1}$) spectra of the 1100-1200 cm^{-1} region of the central part of Jupiter were obtained in 1980 March and 1981 April. The best fit NH_3 distribution curve shows a higher than solar mixing ratio $[NH_3]/[H_2] = (3.3 \pm 1.7) \times 10^{-4}$, below the 147 K layer (> 0.6 atmosphere). If we introduce NH_3 ice particles as an opacity source, the NH_3 mixing ratio below the 147 K layer can be lowered, but the fit is worse than that given by the model excluding NH_3 ice

particles. The best fit PH_3 distribution curve has a $[PH_3]/[H_2]$ mixing ratio of $(8.3 \pm 2.0) \times 10^{-7}$ in the troposphere. We also found a $[CH_4]/[H_2]$ mixing ratio of $(2.5 \pm 0.4) \times 10^{-3}$ in the troposphere. The derived D/H ratio is $3.0^{+1.1}_{-0.8} \times 10^{-5}$. Most of the flux in this spectral region comes from layers above the 170 K level (< 1 atmosphere).

The Astrophysical Journal, 262:388-395, 1982 November 1

THE ABUNDANCES OF ETHANE AND ACETYLENE IN THE ATMOSPHERES OF JUPITER AND SATURN

K. S. Noll and R. F. Knacke
Astronomy Program, Department of Earth and Space Sciences,
State University of New York at Stony Brook

Alan T. Tokunaga
Institute for Astronomy, University of Hawaii

J. H. Lacy
Department of Astronomy, University of Texas, Austin, Texas

S. Beck
Department of Physics, Northeastern University, Boston, MA

and

E. Serabyn
Max Planck Institut für Radio Astronomie, Federal Republic of Germany

Infrared spectra near 780 cm^{-1} of Jupiter and Saturn have been obtained to determine the stratospheric abundances of ethane (C_2H_6) and acetylene (C_2H_2). Atmospheric models using Voyager thermal profiles and density profiles with constant mixing ratios result in the mixing ratios, $X(C_2H_2) = 1.0\ (\pm 0.3) \times 10^{-7}$ and $X(C_2H_6) = 5.5\ (\pm 1.5) \times 10^{-6}$ for Jupiter. The results for Saturn are $X(C_2H_2) = 3.0\ (\pm 1.0) \times 10^{-7}$ and $X\ (C_2H_6) = 7.0\ (\pm 1.5) \times 10^{-6}$. The ratio of ethane to acetylene, $n[C_2H_6]/n[C_2H_2]$, is found to be insensitive to model atmosphere assumptions. The ratio is 55 ± 31 for Jupiter and 23 ± 12 for Saturn from models with uniform mixing ratios. Atmospheric models with density profiles adapted from theoretical photochemical models also result in a higher ratio of ethane to

acetylene (by a factor of 2 at the 1-mbar level) on Jupiter. The lower abundance of acetylene on Jupiter suggests that the rate of vertical transport in the stratosphere may be more rapid on Saturn than on Jupiter.

Icarus 65, 257-263 (1986)

DETECTION OF CARBON MONOXIDE IN SATURN

Keith S. Noll and R. F. Knacke
Astronomy Program, Department of Earth and Space Sciences,
State University of New York at Stony Brook

T. R. Geballe
United Kingdom Infrared Telescope;
and Foundation for Astronomical Research in the Netherlands

and

Alan T. Tokunaga
Institute for Astronomy, University of Hawaii

ABSTRACT

We have investigated six spectral regions containing lines of the CO 1-0 vibration-rotation band near 4.7 μm in Saturn. Three of the lines are free of blending and unambiguously establish the presence of this molecule in Saturn's atmosphere. Two sources of CO are considered; rapid convection from the hot interior and infall of oxygen-bearing material from outside. A uniform distribution of CO, corresponding to an internal origin, yields a mole fraction $q(CO) = 2.0 \pm 0.7 \times 10^{-9}$. This model requires very rapid vertical transport and/or greater abundance of heavy elements in Saturn than in Jupiter. A model with CO confined to the upper atmosphere requires a stratospheric mole fraction of $q(CO) = 3 \pm 1 \times 10^{-7}$. If the infalling material is from the rings, the observed column abundance implies a ring lifetime of only $\sim 10^7 - 10^8$ yr.

The Astrophysical Journal, 309:L91-L94, 1986 October 15

THE ORIGIN AND VERTICAL DISTRIBUTION OF CARBON MONOXIDE IN JUPITER

Keith S. Noll and R. F. Knacke
State University of New York at Stony Brook

T. R. Geballe
United Kingdom Infrared Telescope
and Foundation for Astronomical Research in the Netherlands

and

Alan T. Tokunaga
Institute for Astronomy, University of Hawaii

ABSTRACT

Six lines of the CO 1-0 vibration-rotation band near 4.7 μm have been observed in Jupiter at a resolution of 0.07 cm^{-1} and have been clearly resolved. The measured line profiles indicate that the line-forming region is at a pressure of 2-9 bars. We conclude that CO is present in the troposphere at a mole fraction of $1.6 \pm 0.3 \times 10^{-9}$. It is not concentrated in the stratopshere, as some earlier data had indicated. The presence of CO in the troposphere clearly favors models with rapid vertical mixing as the source of CO. The observed mole fraction of tropospheric CO shows that the global oxygen abundance in Jupiter's gaseous envelope below the cloud-forming regions (specifically, near the 1100 K level) must be near the solar value. Spatially resolved spectra of belt and zone regions, and of the Great Red Spot show no differences in the shapes of absorption lines or in the CO abundance, but they do show large variations in intensity. This implies that intervening clouds with optical depth of 0.5-4 are present above the line-forming region and that the mixing rates are the same in all of the regions we investigated from 1100 K up to the line-forming region (200-300 K) and over scales coarser than 5" (20,000 km).

The Astrophysical Journal, 324:1210-1218, 1988 January 15

EVIDENCE FOR GERMANE IN SATURN

Keith S. Noll and R. F. Knacke
Astronomy Program, Department of Earth and Space Sciences,
State University of New York at Stony Brook

T. R. Geballe
United Kingdom Infrared Telescope
and Foundation for Astronomical Research in the Netherlands

and

Alan T. Tokunaga
Institute for Astronomy, University of Hawaii

ABSTRACT

Six spectra of Saturn obtained in narrow wavelength intervals near 4.7 μm show evidence for absorption by GeH_4, which has not previously been detected in Saturn. We find, from comparison with simulated spectra derived from a model atmosphere, that the mole fraction of germane is $qGeH_4 \sim 4 \pm 2 \times 10^{-10}$. Similar analysis of spectra of Jupiter demonstrates the sensitivity of our model atmosphere program to the abundance of GeH_4. The GeH_4 Q branch at 2111 cm^{-1} appears to be missing when the Saturn spectrum is compared to thermal-only models; but models with a weakly reflecting layer near the tropopause reproduce the observed spectrum in the Q branch region. The Q branch contrast is greatly reduced by the reflecting layer. Thermal flux dominates Jupiter's spectrum but reflected solar radiation is a measurable fraction of Saturn's radiance, especially for spectral regions where the flux falls below ~ 2×10^{-3} erg/cm^2sec sr cm^{-1}. The ν_1 band of AsH3 is proposed as the possible source of an unidentified absorption near 2115 cm^{-1}.

Icarus 75, 409-422 (1988)

ARSINE IN SATURN AND JUPITER

Keith S. Noll
Lunar and Planetary Laboratory, University of Arizona

T. R. Geballe
Joint Astronomy Center

and

R. F. Knacke
Astronomy Program,
State University of New York at Stony Brook

ABSTRACT

We have found a prominent absorption feature in Saturn and Jupiter near 4.7 μm that is coincident with the ν_3 Q-branch of AsH_3. A smaller absorption at the location of the ν_1 Q-branch of AsH_3 is also observed in Saturn. Based on the two spectral coincidences and agreement of the band structure, we conclude that AsH_3 is present in both atmospheres. The mole fractions of AsH_3 are determined to be $qAsH_3 = 1.8^{+1.8}_{-0.9}$ ppb in Saturn and $qAsH_3 = 0.7^{+0.7}_{-0.4}$ ppb in Jupiter, and are probably representative of the As/H ratio in the gaseous envelopes of these planets. Arsenic is significantly enriched over the solar abundance in both planets. Mass-dependent compositional gradients in the atmospheres are ruled out. The ratio of the abundances in the planets, which can be computed without making absolute abundance determinations, suggests that AsH_3 is almost a factor of 2 higher in Saturn than in Jupiter. The observed enrichments are consistent with the core instability model for the formation of the giant planets. Models of arsenic chemistry that predict strong depletions of AsH_3 at temperatures below 370 K are not consistent with the observations, suggesting that vertical convection or perhaps some other mechanism inhibits depletion.

The Astrophysical Journal, 338:L71-L74, 1989 March 15

THE ABUNDANCE OF AsH_3 in JUPITER

Keith S. Noll and Harold P. Larson
Lunar and Planetary Laboratory, University of Arizona

T. R. Geballe
Joint Astronomy Centre, 665 Komohana Street, Hilo, Hawaii 96720

ABSTRACT

We derive a new estimate of the arsenic abundance in Jupiter from ground-based and airborne observations in the region of the AsH_3 Q-branch at 2126 cm^{-1}. We used newly analyzed laboratory comparison spectra at AsH_3 to determine that the mole fraction of AsH_3 in Jupiter's atmosphere is 0.22 ± 0.11 ppb, only 0.5 times the solar abundance and nine times less than the mole fraction found in Saturn. The relative abundance of arsenic in these two planetary atmospheres follows the same pattern found for phosphorous. This similarity may constrain models for the incorporation of heavy elements into the gaseous envelopes of the outer planets.

Icarus 83, 494-499 (1990)

II. Graduate Student Research

The following Ph.D. degrees were awarded based on research under this grant:

Dr. A. T. Tokunaga - "High Resolution Spectroscopy of Jupiter and Saturn at Ten and Twenty Microns" (1976).

Dr. S. J. Kim - "Deuterium to Hydrogen Ratio in the Atmospheres of Jupiter and Titan" (1982).

Dr. K. S. Noll - "Carbon Monoxide and Disequilibrium Dynamics in Saturn and Jupiter" (1987).

Noll was also supported by a NASA Graduate Student Award, NGT-33-015-803.

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